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EFFECT OF CORROSION ON THE FATIGUE BEHAVIOR OF 2024-T4 ALUMINUM ALLOY

CLAYTON L. HARMSWORTH

DIRECTORATE OF MATERIALS AND PROCESSES

JULY 1961

AERONAUTICAL SYSTEMS DIVISION

UNCLASSIFIED

Directorate of Materials and Processes, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio
EFFECT OF CORROSION ON THE FATIGUE BEHAVIOR OF 2024-T4 ALUMINUM ALLOY, by Clayton L. Harmsworth. July 1961, 37 p. incl illus. (Proj. 7381; Task 73812) (ASD TR 61-121) Unclassified report

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JULY 1961

PROJECT No. 7381
TASK No. 73812

AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared by the Materials Information Branch, Applications Laboratory. The work was initiated under Project No. 7381, "Materials Application", Task No. 73812, "Data Collection and Correlation". It was administered under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division with Mr. C.L. Harmsworth acting as the project engineer.

This report covers work from September 1959 to March 1961.

The author wishes to acknowledge with appreciation the assistance and advice given by Dr. Frank Beck of the Department of Metallurgy, Ohio State University and Mr. Larry Alessandro of Materials Central.

ABSTRACT

An investigation was conducted to determine the effect of corrosion pitting on the fatigue behavior of 2024-T4 aluminum alloy and to establish a method of measuring pitting corrosion damage with respect to fatigue.

It was found that surface roughness measurements could be used to give a useful indication of the fatigue life that may be expected from a corroded structural member of 2024-T4 aluminum. The effect of pre-existing corrosion on the mechanism of fatigue was determined to be largely that of a stress raiser. In the case of pitting corrosion, calculations could be made, based upon critical pit measurements, to determine the stress concentration effect of the corrosion pit.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

D.A. Shinn

D.A. SHINN
Chief, Materials Information Branch
Applications Laboratory
Directorate of Materials and Processes

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I. INTRODUCTION

The design of modern advanced weapon systems demands structures that are lighter and stronger with an ever increasing emphasis on more realistic margins of safety. The critical factor in the design of many of these advanced systems is an accurate knowledge of fatigue behavior in the expected environment.

If this environment produces surface discontinuities the fatigue properties of the material will be affected. Corrosion has long been recognized as an extremely critical factor in its effect on fatigue life of a structure. Because of the many complexities evolved in the corrosion-fatigue relationship, little useful engineering data are available.

The purpose of this program therefore was: (1) To analyze the mechanism of corrosion-fatigue failure, (2) To establish a useful measure of corrosion damage with respect to fatigue behavior, and (3) To obtain some useful engineering data which can be used with a realistic degree of confidence in estimating the fatigue life of corroded 2024-T4 aluminum alloy.

II. CRITERIA FOR CORROSION-FATIGUE INVESTIGATION

Any program designed to furnish significant engineering data for a structure in a corrosive environment (including air) must consider the relationship of corrosion to the fatigue stress pattern, the environmental conditions, both physical and chronological, to which the material is subjected, and finally to the variance of the test results and the service conditions.

Inasmuch as the above considerations may have a serious effect upon any corrosion-fatigue program they are discussed in detail.

A. Corrosion-Fatigue-Stress Relationship

In general the principal effect of corrosion (pitting or otherwise) is that of a stress raiser. In this investigation the corrosion attack was from pitting. These pits served as stress raisers which increased localized stress above the normal applied value, and accelerated fatigue failure in much the same manner as in notched fatigue specimens. At applied stresses below the endurance limit the corrosion discontinuities could raise the localized stresses to a value greater than that for crack initiation and cause failure.

B. Environment

Formation of the stress raisers is a function of the nature of the corrosion attack. This report considers only pitting corrosion which is one of the most critical forms of corrosion in weapon system applications. However, all forms of corrosion may to some extent promote stress concentrations.

Often overlooked by investigators when applying corrosion fatigue test results to service applications is the important chronological relationship between corrosion and applied

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stress. For example, although pre-existing corrosion pits generally serve as stress raisers forming nuclei for fatigue damage as previously mentioned, fatigue cracks may also form cavities in which corrosion is concentrated and/or accelerated, or the two mechanisms may take place simultaneously. While the vast majority of service failures are results of stress acting on the previously corroded area, many investigators have obtained test data under simultaneous conditions of corrosion and stress and have erroneously attempted to apply this data to service conditions involving pre-existing corrosive damage. An example would be a weapon system located near a coastal area, in which case the system would have been subjected to a corrosive environment in a relatively unstressed condition. The fatigue loads would generally be applied after corrosion had damaged the part and in the majority of cases the loads would be applied during flight, and away from the original corrosive environment.

C. Significance of Data

Both fatigue and corrosion data are noted for their scatter. Consequently, any attempt to establish usable relationships should include test data of a reasonable level of confidence. Without this level of confidence erroneous assumptions could be made and, the resulting data would not be satisfactory for design or for service applications.

III. TESTING PROCEDURE

A. Materials

The material used for this investigation was 2024-T4 aluminum alloy. This is a common airframe structural material with the chemical composition shown in table 1. Its tensile properties are shown in table 2. It is relatively ductile and less sensitive to discontinuities than many of the higher strength materials. Consequently, the effects of equal amounts of corrosion on the fatigue properties of the more sensitive materials should normally be more severe. Therefore, results of this investigation should not be applied to other materials to obtain design data. Approximately 85 rotating beam and 12 tensile specimens were machined from a single heat of 2024-T4. The rotating beam configuration is shown in figure 1. The specimens were machine polished in a longitudinal direction to a surface finish of approximately 5 to 10 microinches, root mean square (rms).

Seven additional specimens were drilled to simulate corrosion pits with theoretical stress concentration factors (K_t) from 1.8 to 2.8. The pits were drilled to depths of .0020 to .0158 inches. The drill point was ground to produce a notch root radius of .006 inches rather than the conventional 60 degree "V" notch impression.

B. Environment

The tapered ends of the specimens were coated with paraffin to prevent corrosion on the ends that mount into the fatigue machine. Several specimens are shown in figure 2. The specimen gage sections were then cleaned with carbon tetrachloride to remove even a trace of the paraffin film, and then rinsed with distilled water. The specimens were suspended in a salt spray environment chamber as shown in figure 3, which was maintained at a temperature of 95°F ± 2°F during the exposure period. The salt solution consisted of 20 percent (by weight) of NaCl in de-ionized water. The specimens were removed from the environment chamber after various time periods of exposure (2 hours to 32 days). When removed from the environment chamber the specimens were rinsed in distilled water, dried and fatigue tested. The period of time between the removal from the environment chamber and the beginning of the fatigue tests never exceeded 24 hours.

C. Fatigue Tests

The fatigue tests were performed at room temperature (72°F, ±2°F) in four R.R. Moore rotating beam machines operating at 3600 rpm. Two of these machines are shown in figure 4. Although the machines were carefully calibrated, the results were statistically checked for any possibility of machine variability in accordance with standard practice. (1) No significant variations were found. A stress of ±26,000 psi was chosen to induce failure at a selected number of cycles on the predicted S/N curve. This selection was made to prevent runouts past the endurance limit (10^8 cycles). A few tests were conducted at ±40,000 psi and ±50,000 psi to obtain a limited amount of comparative data at other stress levels.

Considerable thought was given to the relative advantages of axial loading versus rotating beam specimens. Axial loading generally gives a more accurate estimate of the fatigue properties of a material due to a more uniform stress distribution transversely through the specimen gage section. On the other hand rotating beam tests are generally more responsive to surface conditions, more economical, and consequently more applicable to statistical analysis. In view of the latter, rotating beam tests were used in this investigation.

D. Measurement Techniques

The critical pit depths were measured on the fracture surface using a toolmaker's microscope. The root radii of the critical areas of the corrosion pits were measured by examining a longitudinal section through the critical pit with a 200 X microscope, with a vernier scale. Measurement of surface roughness was made with a conventional profilometer.

E. Statistical Procedures

The variance in corrosion and fatigue data necessitated the use of statistics to assess the meaning of the test results. Therefore the data is presented in accordance with ASTM quality control recommendations. (2) Five specimens were allocated for each major test group as shown in tables 3, 4 and 5. It has generally been conceded that fatigue life at a constant stress approximates a log normal rather than a normal distribution. Consequently the average life values and standard distributions summarized in table 3 are based on log normal distributions. The average rms values for each group of 8 specimens are based on a log normal distribution. Average theoretical stress concentration values (K_t) are based on a normal distribution.

The average log normal values were calculated from equation (1). The corresponding standard deviations with respect to a log normal distribution of fatigue life ($\sigma_{\log x}$) were calculated from equation (2). Scatter limits are plotted as two standard deviations as shown in figure 17. An example of the calculation of these limits is shown in table 7.

$$\overline{\log x} = \frac{\sum_{i=1}^{n} \log x_i}{n} \tag{1}$$

$$\sigma_{\log x} = \sqrt{\frac{\sum_{i=1}^{n} (\log x_i)^2}{n} - (\overline{\log x})^2} \tag{2}$$

Where:

$\sum_{i=1}^{n} \log x_i$ = the sum of the log of all values of x from x_1 to x_n inclusive

x = fatigue life

$\bar{x}$ = average fatigue life

n = number of specimens

σ = one standard deviation

IV. DISCUSSION OF RESULTS

A. Surface Roughness as a Measure of Pitting Corrosion with Respect to Fatigue

In order that corrosion-fatigue data may have any value from a service application standpoint, a simple measurement of corrosion must be established. This measurement must be a nondestructive one that can be made a part of the periodic service inspection of a weapon system. It must give results that can be used to determine the limitations that may be imposed upon a corrosion pitted structural member. Certain methods considered included: estimating the density of corrosion pits, hardness checks, service record analysis, and surface roughness measurements.

Measurements based upon estimating the density of corrosion pits, were eliminated because of the difficulty in making readings under mild conditions of corrosion. Other disadvantages were the poor reproducibility of measurements with various operators and lack of information concerning the depth of pitting.

Hardness measurements were eliminated as hardness checks on the corroded specimens showed little correlation with the fatigue data. Also, it was feared that hardness indentation marks on a structure might cause undesirable stress raisers.

An analysis of service records would be acceptable only if the severity of corrosion remained a constant value from day to day as maintained in the test chamber. Figure 17 shows the fatigue life of specimens with respect to duration of exposure. While these data show correlation of time with respect to exposure, the effect of a varying exposure condition encountered at a coastal launching pad or airport would make the use of these data extremely unreliable. For example, the intensity of the test exposure employed here is much greater than that which would be encountered in any climatic condition.

Surface roughness measurement seems to be the most usable technique to link service behavior with test results on 2024-T4 aluminum alloy. Surface roughness increases as a function of exposure time under constant environment conditions as shown by figure 18. Statistical analysis using the t-test showed the increasing surface roughness values with increasing exposure time to be significant. Surface roughness also serves as a good indication of fatigue life at various stress levels as shown in figure 19. While it is felt that the data in figure 19 can be used to make useful predictions of the service life of corroded 2024-T4 aluminum, it should be re-emphasized that these data cannot be used to predict the behavior of other materials. Separate curves similar to those shown in figure 19 would be required for each material considered.

The above method could, of course, be applied only to service applications where the corrosion precedes the application of load. Neither this nor any other existing method of analysis is reliable enough to use at present to determine the fatigue life of a corroded structural member that has been subjected to previous fatigue loading of various degrees during its life cycle.

B. Calculation of K_t of Critical Corrosion Pits

Although surface roughness has been shown to be a useful indication of the fatigue resistance of corroded 2024-T4 aluminum alloy, this is strictly an empirical relationship. A stress analysis of the corroded area is necessary to establish a better understanding of the effect that pre-existing corrosion has on fatigue. An examination at high magnification of the failed surfaces similar to those shown in figures 9 through 16 indicates that a single corrosion pit is generally responsible for the initiation of failure. Although several specimens with surface roughness values over 100 microinches (rms) had fatigue cracks initiating from more than one pit on the fracture surface, the final analysis indicated one pit could be considered as critical.

Several methods of conducting a stress analysis of the corrosion pits were considered. The most satisfactory procedure was to consider a longitudinal section through the critical corrosion pit. The stress pattern in this section is then adaptable to Neuber's stress analysis for a shallow groove in bending. (3) "Equivalent" K_t values of the corrosion pits can then be calculated using measured values of pit depth and root radius.

The fatigue lives of the corrosion pitted specimens were checked with fatigue lives of specimens which were drilled or had artificially pitted surfaces with accurately known pit depths and root radii. The fatigue lives of these specimens fell within the same scatter band as that for the corroded specimens with equal K_t values. The fatigue properties of these artificially pitted specimens are listed in table 6.

The above stress analysis did not include the effect of the supporting unnotched material on each side (transverse to the direction of load) of the corrosion pit, nor did it consider the effect of adjacent corrosion pits on the stress pattern of the critical pit. The fatigue life results were, however, compared with results on conventionally notched specimens of similar material which were obtained from the literature. While the scatter between groups of specimens from the literature was too great to draw any significant comparisons to serve as a check in the above stress analysis, most available data did fall within, or slightly to the left, of the K_t values shown in figure 20. For example, Spretnak and Fontana (4) conducted tests on 2024-T4 0.50 inch diameter notched specimens in bending. These specimens had a K_t value of 3.15. At ±26,000 psi they had a fatigue life of 200,000 cycles. The average fatigue life of corrosion pitted specimens with an "equivalent" K_t of 3.15 is approximately 260,000 cycles.

Several interesting observations were noted in correlating the results of the test data with the stress analysis. It was observed that the width of the critical pit in the longitudinal direction had little effect on the test results. Examination of these pits under high magnification, as shown in figures 5 and 6, showed that all cracks appeared to initiate from areas of corrosion or stringers which branched off from the main corrosion pit. Random measurement of the tip of these branches resulted in a relatively constant radius value of .0050 inch regardless of the depth of the pit or the length of exposure time. This radius value of .0050 inch was used in calculating all the "equivalent" K_t values.

Additional observations revealed that the number of secondary pits initiating fatigue damage had relatively little effect on the results. For example, specimens exposed for 32 days had from 2 to 6 corrosion pits which initiated some degree of fatigue damage (see figure 15). However, there was no more scatter in the cyclic life, (figure 17) or "equivalent" K_t values (figure 21), from this group than from the specimens exposed 8 hours (see figure 9), all of which had only one visible corrosion pit initiating fatigue damage.

C. Tensile Behavior

The ultimate tensile and yield strength of the specimens showed no significant decrease after 32 days exposure to the pitting environment. However, the average decrease in elongation was approximately 19.6 percent and the average decrease in reduction in area was approximately 44.5 percent. This rather severe decrease in ductility compares with a loss in fatigue strength of approximately 12 to 21 percent within the range of $3X10^4$ to 10^6 cycles. The tensile specimens had a diameter of .500 inch while the fatigue specimens were .300 inch in diameter.

V. SUMMARY AND CONCLUSIONS

Surface roughness measurements serve as a useful indication of the fatigue life of 2024-T4 aluminum damaged by pitting corrosion. Further effort will be necessary to determine the applicability of surface roughness measurements to other materials.

Corrosion-fatigue may be classified as: (1) pre-existing corrosion on dynamically-stressed members, (2) the simultaneous action of dynamic stress and corrosion, and (3) corrosion on previously fatigue-stressed material. Most cases involving aircraft and missiles are of the first category where pre-existing corrosion discontinuities cause stress concentrations, which accelerate fatigue damage due to higher local stress. In the case of pitting corrosion the stress concentration effect of these pits may be calculated with a reasonable degree of accuracy, through the proper use of Neuber's analysis for a grooved notch.

Pitting corrosion had little, if any, effect on the ultimate tensile and yield strength of 2024-T4; however, the ductility was significantly reduced as indicated by reduction in elongation and reduction in area measurements.

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Table 1

Chemical Composition of 2024-T4 Aluminum Alloy used in
Corrosion Fatigue Investigation

Cu	Fe	Si	Mn	Mg	Zn	Cr	Ti
4.08	0.34	0.15	0.57	1.42	0.03	0.02	0.03

Table 2

Tensile Properties of 2024-T4 Aluminum Alloy After Exposure to a
Pitting Corrosive Environment

Spec. No.	Exposure Time	Ult. Ten. Str. psi	Yield Str. psi (0.2%)	Elong % 2" gage	Red. in Area %
1-1	0	72,550	50,800	16.5	12.1
2-1	0	71,800	49,100	16.2	9.2
5-1	0	71,300	48,300	18.5	12.3
3-1	0	70,300	50,100	15.8	10.4
1-2	1 Day	72,600	49,850	16.2	9.6
1-3	1 Day	72,350	52,300	15.7	8.6
3-3	1 Day	71,350	50,300	14.5	8.4
3-4	8 Days	70,200	49,250	13.0	10.4
2-2	8 Days	69,950	49,300	13.5	6.8
2-3	8 Days	69,400	49,000	10.9	10.9
5-4	32 Days	71,050	49,300	12.5	5.6
5-3	32 Days	70,800	48,400	16.5	6.5
3-2	32 Days	70,500	50,300	11.5	4.9
5-2	32 Days	70,250	49,100	13.0	7.6

Table 3

Summary of The Statistical Properties of 2024-T4 Fatigue Specimens Exposed to a Pitting Corrosive Environment and Stressed at ±26,000 psi

Exposure Time	Avg. Cycles To Failure (Log Normal Dist.)	*±2 Standard Deviations (Log Normal Dist.)	**Avg. Surface Roughness (Log Normal Dist.)	Avg. K_t (Normal Dist.)	No of Samples
0	5,598,000	+15,890,000 - 6,082,000	8.6	1	5
2 Hours	7,825,000	+15,370,000 - 3,984,000	11.9	1	5
4 Hours	1,688,000	+ 3,510,000 - 810,700	12.7	1.79	5
8 Hours	967,400	+ 2,734,000 - 342,300	14.2	2.12	5
1 Day	747,300	+ 1,045,000 - 534,500	23.2	2.41	5
2 Days	813,900	+ 2,548,000 - 254,100	32.3	2.50	5
4 Days	489,900	+ 893,500 - 269,300	56.9	2.62	5
8 Days	597,800	+ 778,700 - 459,000	66.8	2.72	5
16 Days	417,300	+ 755,300 - 230,600	86.8	2.89	5
32 Days	443,400	+ 631,600 - 311,300	138.2	3.02	5

* Values shown are high limit (+) and low limits (-) which are computed as ± 2 from the average cycles to failure.

** Average surface roughness values are rms values measured in microinches assuming a log normal distribution.

Table 4

Fatigue Properties of 2024-T4 Aluminum Alloy Subjected to Exposure In a Pitting Environment and Stressed at ±26,000 psi

Spec No	Exposure Time	Cycles to Failure	Surface Roughness microinches (rms)	Pit Depth Inch	K_t	Machine No
2-3	0	23,604,900	6	-----	1	2
3-1	0	6,293,000	11	-----	1	1
2-2	0	5,623,000	9	-----	1	4
1-16	0	2,722,300	13	-----	1	2
3-2	0	2,418,400	11	-----	1	1
3-6	2 Hours	14,892,500	13	-----	1	1
1-6	2 Hours	7,644,000	12	-----	1	2
2-4	2 Hours	7,237,300	13	-----	1	2
5-12	2 Hours	6,021,400	10	-----	1	1
5-11	2 Hours	5,920,000	12	-----	1	3
5-13	4 Hours	2,744,900	13	.0004	1.6	3
2-6	4 Hours	2,117,400	12	.0007	1.75	1
1-27	4 Hours	1,938,200	10	.0003	1.6	1
3-7	4 Hours	1,101,900	14	.0014	2.0	4
2-5	4 Hours	1,100,000	15	.0015	2.0	1
1-19	8 Hours	1,766,100	18	.0012	1.9	1
1-17	8 Hours	1,608,200	12	.0014	2.0	3
2-21	8 Hours	896,300	13	.0027	2.35	2
5-18	8 Hours	781,400	12	.0013	1.95	3
3-22	8 Hours	426,100	17	.0028	2.4	2
5-20	1 Day	1,006,600	23	.0020	2.15	3
3-8	1 Day	780,100	25	.0036	2.55	4
2-7	1 Day	717,500	25	.0022	2.2	1
3-9	1 Day	674,500	13	.0031	2.45	4
5-14	1 Day	613,300	36	.0041	2.6	3
3-11	2 Days	2,247,200	28	.0021	2.2	2
1-4	2 Days	907,400	33	.0035	2.5	-
5-15	2 Days	703,800	35	.0034	2.5	2
3-10	2 Days	611,100	23	.0051	2.7	3
2-8	2 Days	407,200	47	.0041	2.6	1
2-20	4 Days	776,300	57	.0044	2.6	-
3-12	4 Days	498,100	76	.0040	2.6	3
2-10	4 Days	491,900	45	.0041	2.6	2
5-10	4 Days	491,100	47	.0041	2.6	1
2-9	4 Days	301,800	65	.0048	2.7	3

Table 4 (Cont'd)

Spec No	Exposure Time	Cycles to Failure	Surface Roughness microinches (rms)	Pit Depth Inch	K_t	Machine No
3-13	8 Days	690,000	75	.0061	2.85	2
1-15	8 Days	659,000	95	.0043	2.6	1
5-19	8 Days	613,700	62	.0056	2.8	4
1-21	8 Days	580,700	50	.0043	2.6	4
2-11	8 Days	471,400	60	.0052	2.75	3
5-21	16 Days	555,300	90	.0053	2.75	3
3-14	16 Days	542,500	80	.0057	2.8	3
2-12	16 Days	390,300	85	.0056	2.8	1
1-22	16 Days	376,300	85	.0075	3.0	4
5-17	16 Days	286,100	95	.0093	3.1	4
1-18	32 Days	531,300	190	.0074	2.9	2
5-16	32 Days	505,700	130	.0078	3.0	3
1-20	32 Days	448,000	150	.0068	2.9	4
3-15	32 Days	444,500	170	.0094	3.1	1
2-13	32 Days	320,300	80	.0116	3.2	4

Table 5

Fatigue Properties of 2024-T4 Aluminum Alloy Subjected to a Pitting Environment and Stressed at Loads Other Than ±26,000 psi

Specimen No.	Exposure Time	Fatigue Stress psi	Cycles To Failure	Surface Roughness microinches (rms)
2-23	0	40,000	185,500	9
3-20	0	40,000	146,900	12
3-18	0	40,000	110,600	11
1-5	8 Hours	40,000	196,600	13
2-14	8 Hours	40,000	135,900	16
3-4	8 Hours	40,000	111,000	19
3-19	2 Days	40,000	172,300	19
5-6	2 Days	40,000	112,400	18
1-14	2 Days	40,000	57,600	20
5-9	32 Days	40,000	78,200	145
3-21	32 Days	40,000	75,500	140
3-5	32 Days	40,000	71,200	110
1-3	0	20,000	None at $2X10^7$	-
1-2	0	20,000	None at $2X10^7$	-
1-1	0	20,000	None at 10^8	-
2-1	0	20,000	None at 10^8	-
1-7	0	50,000	36,500	8
1-11	0	50,000	33,800	10
1-9	0	50,000	32,200	9
5-7	8 Hours	50,000	17,200	14
3-23	8 Hours	50,000	14,200	20
2-17	8 Days	50,000	12,700	68
2-22	8 Days	50,000	12,400	58
2-16	8 Days	50,000	10,100	46
3-24	32 Days	50,000	12,100	130
5-8	32 Days	50,000	11,300	120

Table 6

Fatigue Properties of Artificially Pitted (Drilled) 2024-T4 Aluminum Alloy Specimens Stressed at ±26,000 psi

Specimen No.	Cycles To Failure	Pit Depth Part of Inch	Root Radius Part of Inch	K_t
3-16	2,292,500	.0020	.0058	1.8
5-3	1,757,100	.0031	.0066	2.0
1-8	580,800	.0067	.0063	2.45
3-25	746,700	.0091	.0064	2.6
1-10	503,600	.0124	.0069	2.6
2-19	293,100	.0131	.0065	2.8
5-2	542,200	.0158	.0064	2.8

Table 7

Example Calculation of Average Fatigue Life and ± 2 Standard Deviation Limits (2 hour exposure data)

Cycle life	Log of life	$(\text{Log})^2$ of life
14,892,000	1.1729	1.3757
7,644,000	.8833	.7802
7,237,000	.8595	.7387
6,021,000	.7797	.6079
5,920,000	.7723	.5964

$\sum \text{logs} = 4.4677$ $\qquad \sum (\log)^2 = 4.0989$

$\div 5$ $\qquad \div 5$

$\overline{\log} = .8935$ $\qquad \dfrac{\sum (\log)^2}{n} = .8198$

$(\overline{\log})^2 = .7983$

$$\begin{array}{r} .8198 \\ -.7983 \\ \hline .0215 \end{array}$$

$\sqrt{.0215} = .1466$

$2 \times .1466 = .2932$

$$\begin{array}{r} .8935 \\ +.2932 \\ \hline 1.1867 \end{array} = \text{log high limit} \qquad \begin{array}{r} .8935 \\ -.2932 \\ \hline .6003 \end{array} = \text{log low limit}$$

15,370,000 = high limit cycles

.8935 = log average

3,984,000 = low limit cycles

7,825,000 = average cycles

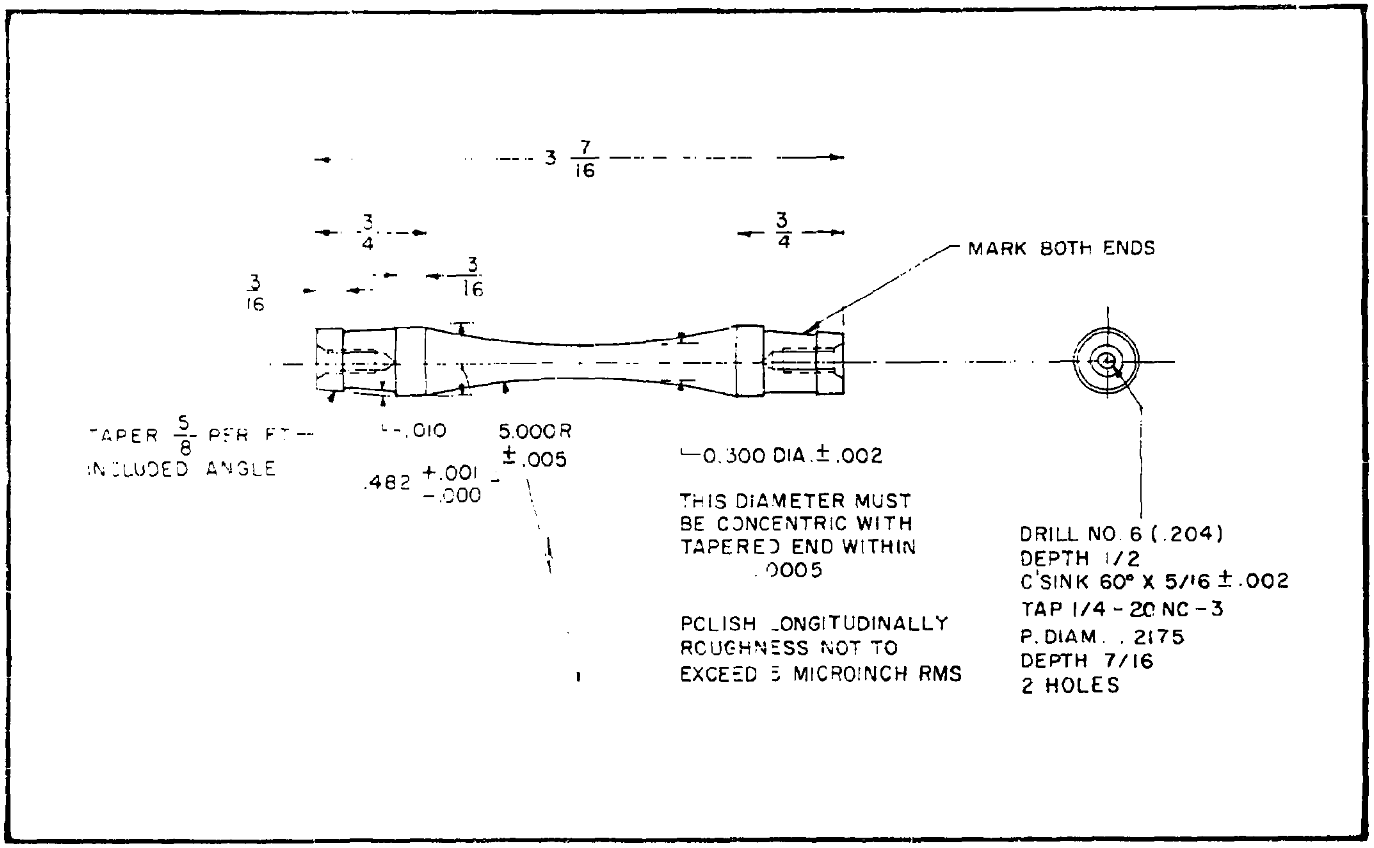

Figure 1. Rotating Beam Configuration

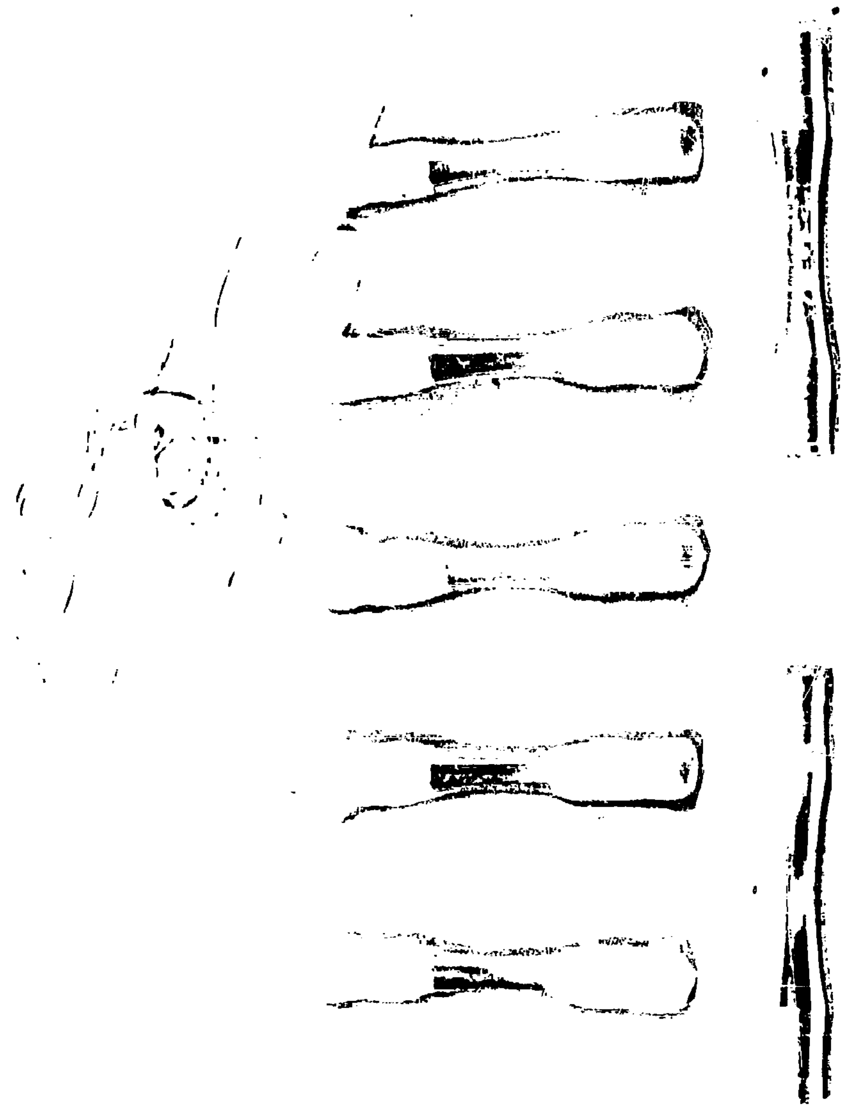

Figure 2. Specimens with Paraffin Coated Ends

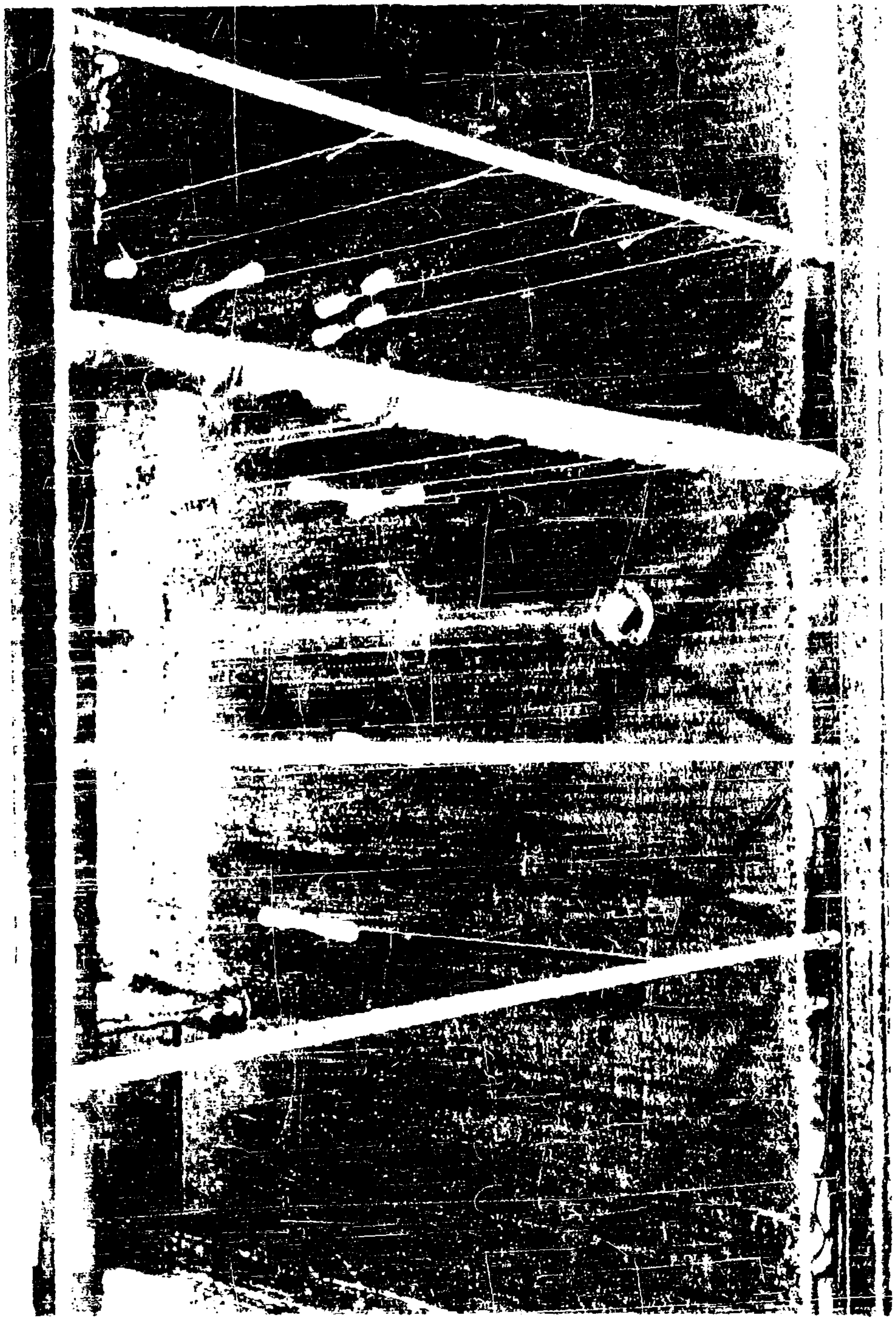

Figure 3. Salt Spray Environment Chamber

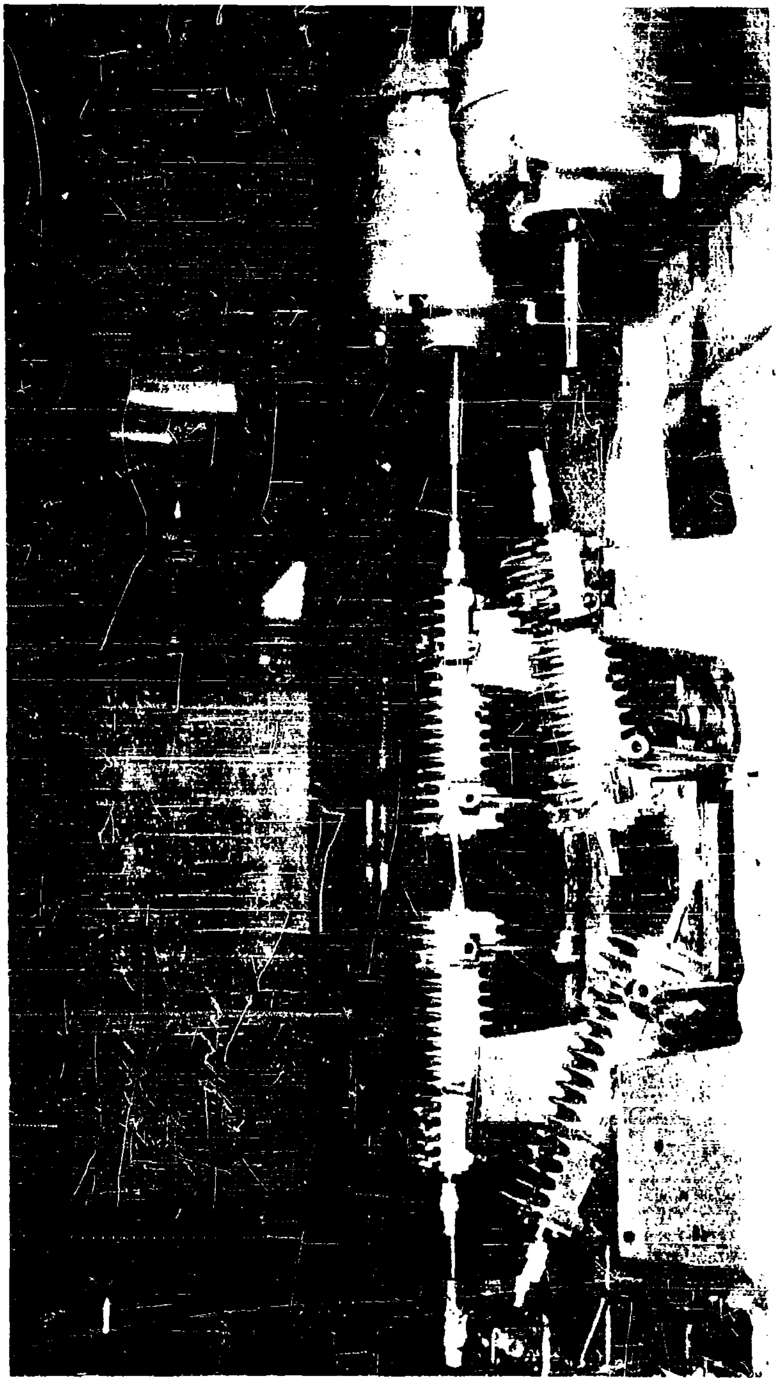

Figure 4 R.R. [illegible] Beam Machines

Figure 5. Fatigue Crack Initiating from Critical Corrosion Pit. Same Surface as shown in fig. 6 with Specimen Halves joined after Failure. Specimen No. 1-21, 200X

Figure 6. Corrosion Pit on Specimen Illustrated in fig. 5 with no Visible Evidence of Fatigue Damage. Located 1/4 inch from Fracture Surface. Specimen No. 1-21, 200X

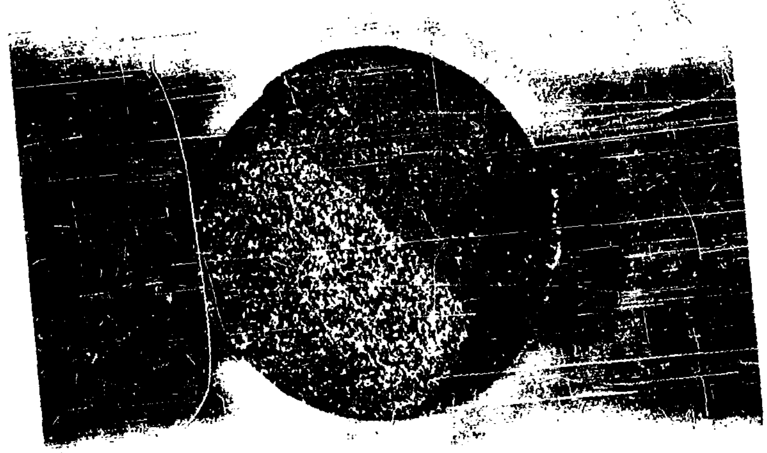

Figure 7. Failure Surface on an Uncorroded 2024-T4 Aluminum Specimen Cycled to Failure at 126,000 psi

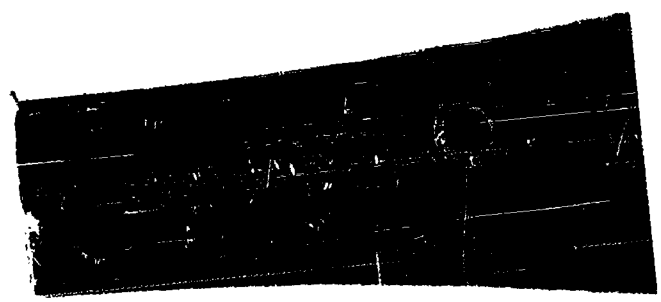

Figure 8. Macrograph of Specimen Illustrated in fig. 7 Showing Polished Surface

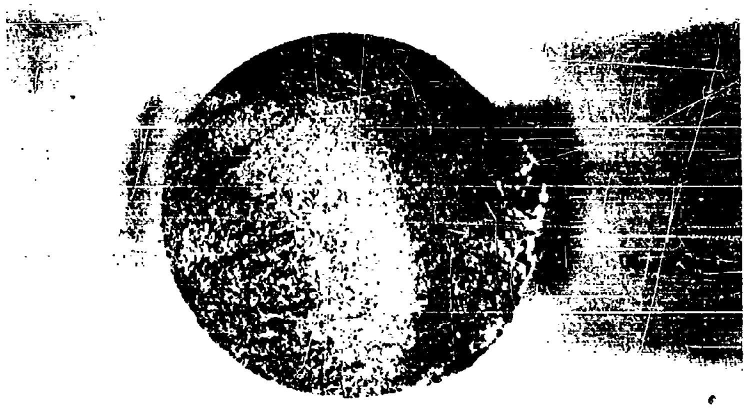

Figure 9. Failure Surface of a 2024-T4 Aluminum Specimen after Exposure to a Corrosive Environment for 8 Hours and Cycled to Failure at ±26,000 psi Specimen No. 1-19, 7X

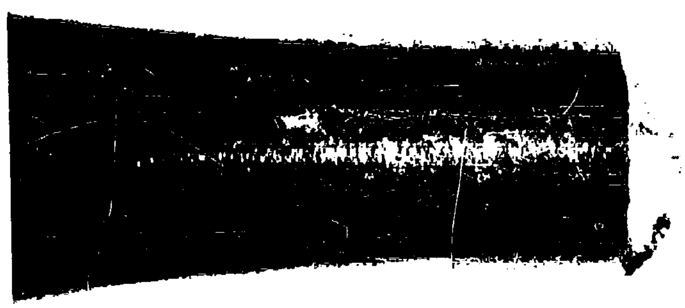

Figure 10. Macrograph of Specimen Illustrated in fig. 9 showing Surface Corrosion. Specimen No. 1-19, 5X

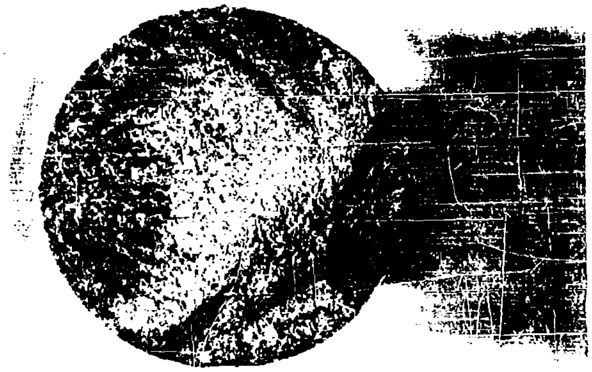

Figure 11. Failure Surface of a 2024-T4 Aluminum Specimen after Exposure to a Corrosive Environment for 1 Day and Cycled to Failure at ±26,000 psi. Specimen No. 2-7, 7X

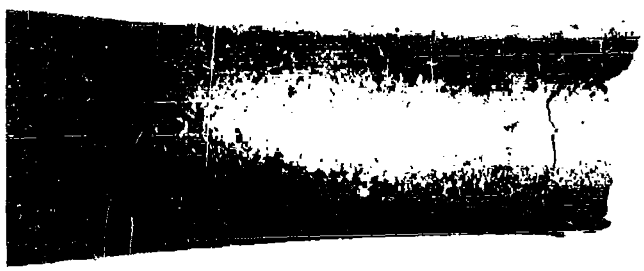

Figure 12. Macrograph of above Specimen Illustrated in fig. 11 showing Surface Corrosion. Specimen No. 2-7, 5X

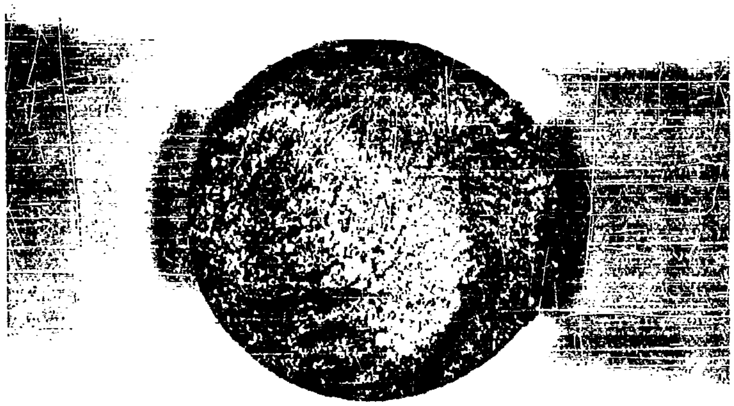

Figure 13. Failure Surface of a 2024-T4 Aluminum Specimen after Exposure to a Corrosive Environment for 8 Days and Cycled to Failure at ±26,000 psi. Specimen No. 1-21, 7X

Figure 14. Macrograph of above Specimen Illustrated in fig. 13 showing Surface Corrosion. Specimen No. 1-21, 5X

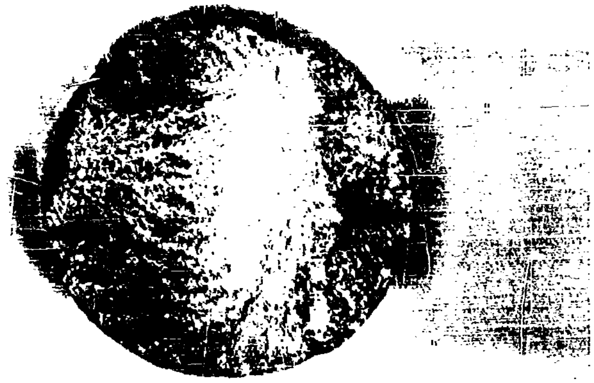

Figure 15. Failure Surface of a 2024-T4 Aluminum Specimen after Exposure to a Corrosive Environment for 32 Days and Cycled to Failure at ±26,000 psi. Specimen No. 3-15, 7X

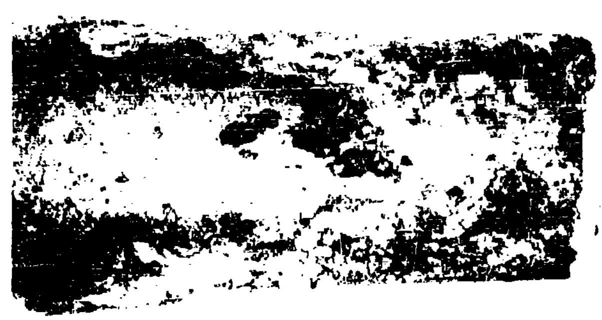

Figure 16. Macrograph of above Specimen Illustrated in fig. 15 showing Surface Corrosion. Specimen No. 3-15, 5X

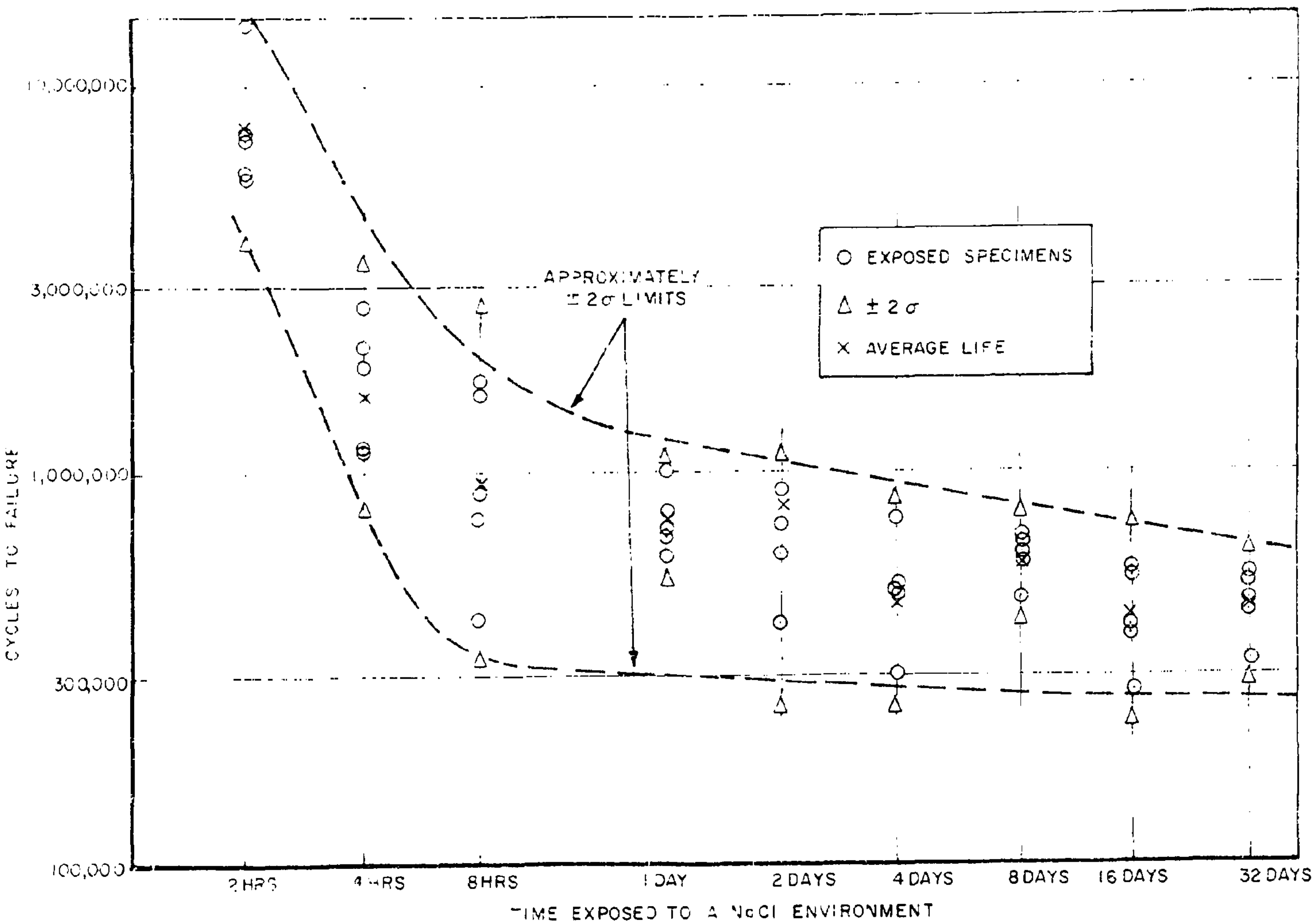

Figure 17. Effect of Exposure Time in a Corrosive Environment on the Fatigue Life of 2024-T4 Aluminum Alloy at 26,000 psi

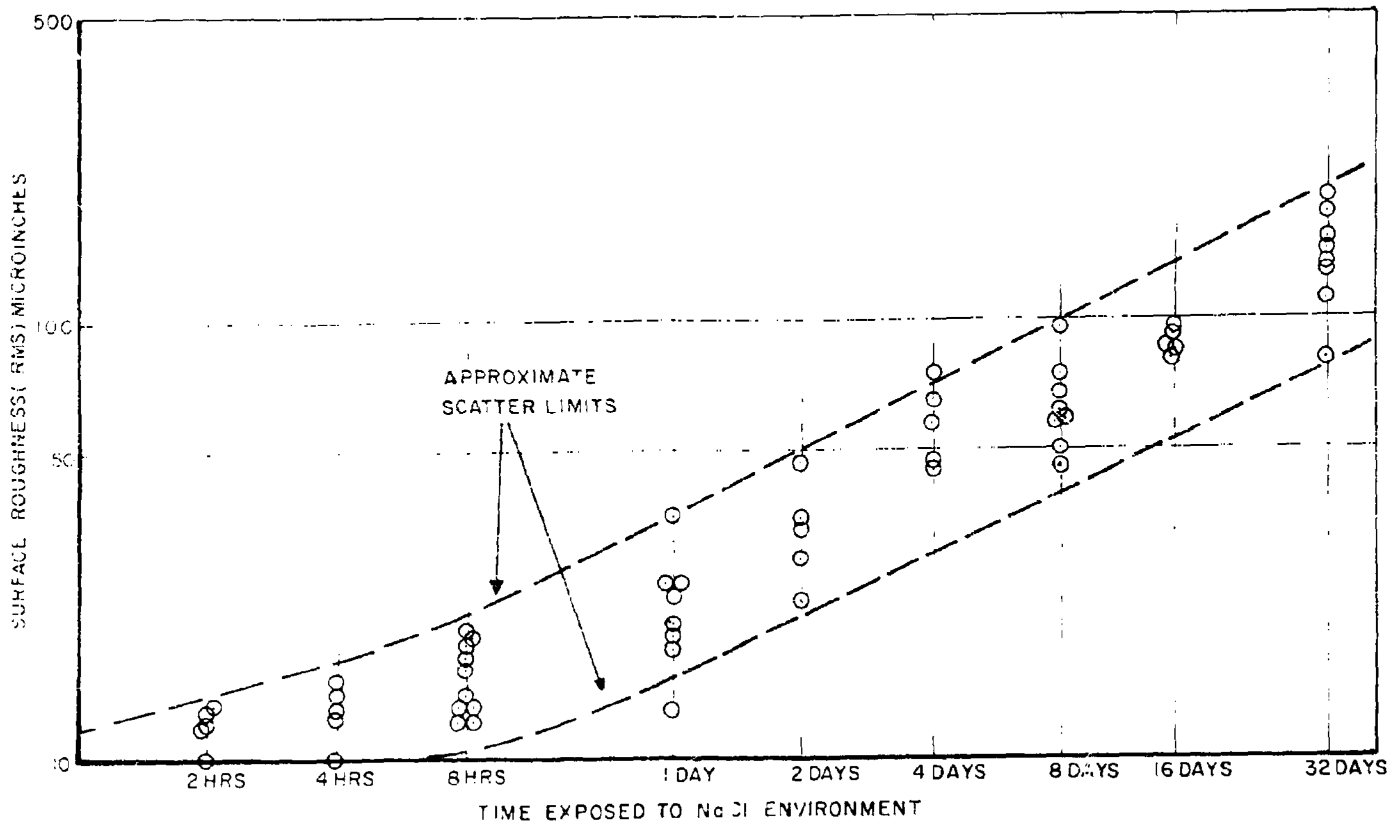

Figure 18. Effect of Exposure Time in a Corrosive Environment on the Measured Surface Roughness of 2024-T4 Aluminum Alloy

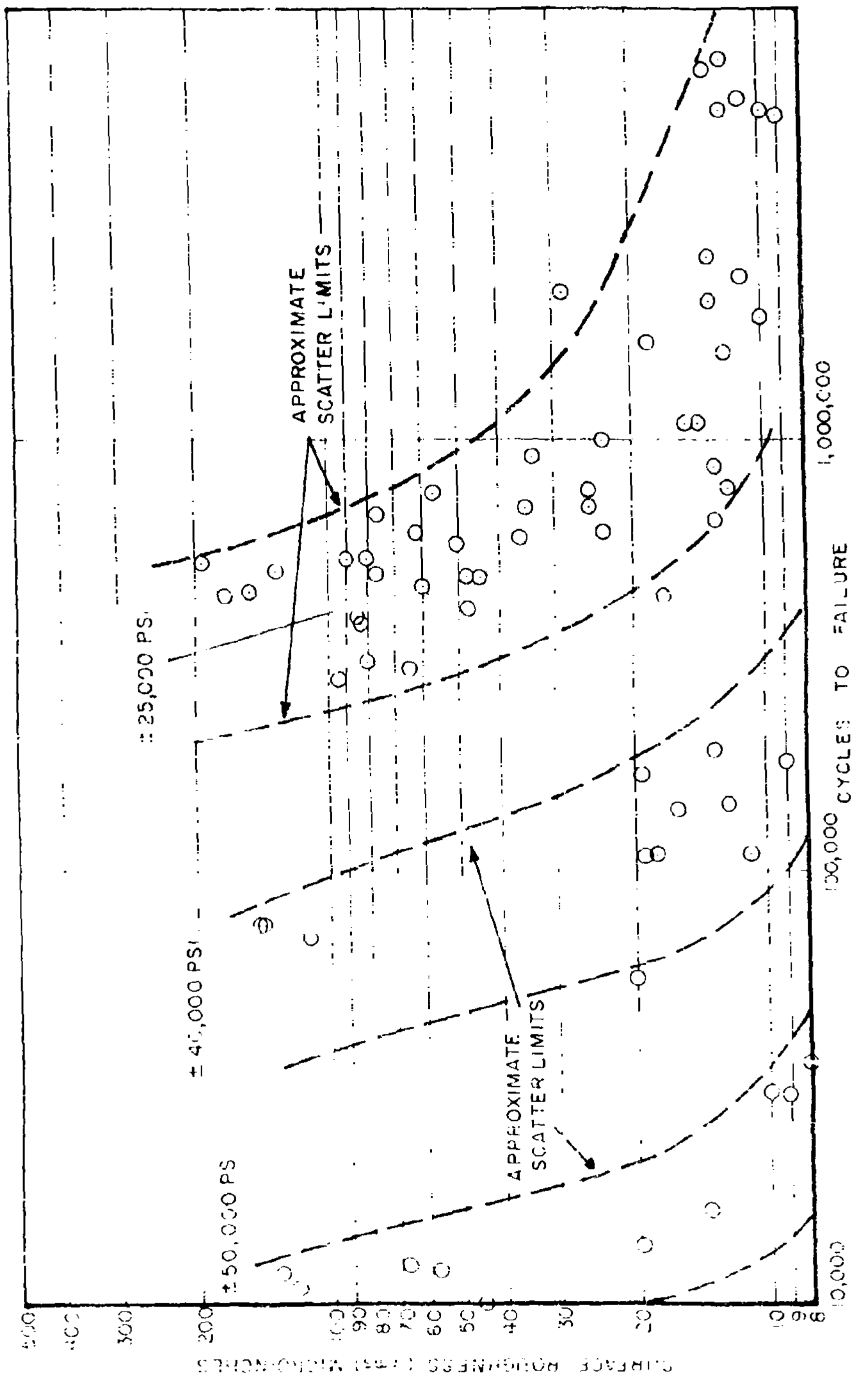

Figure 19. Effect of Surface Roughness on the Fatigue Properties of 2024-T4 Aluminum Alloy at Various Stress Levels

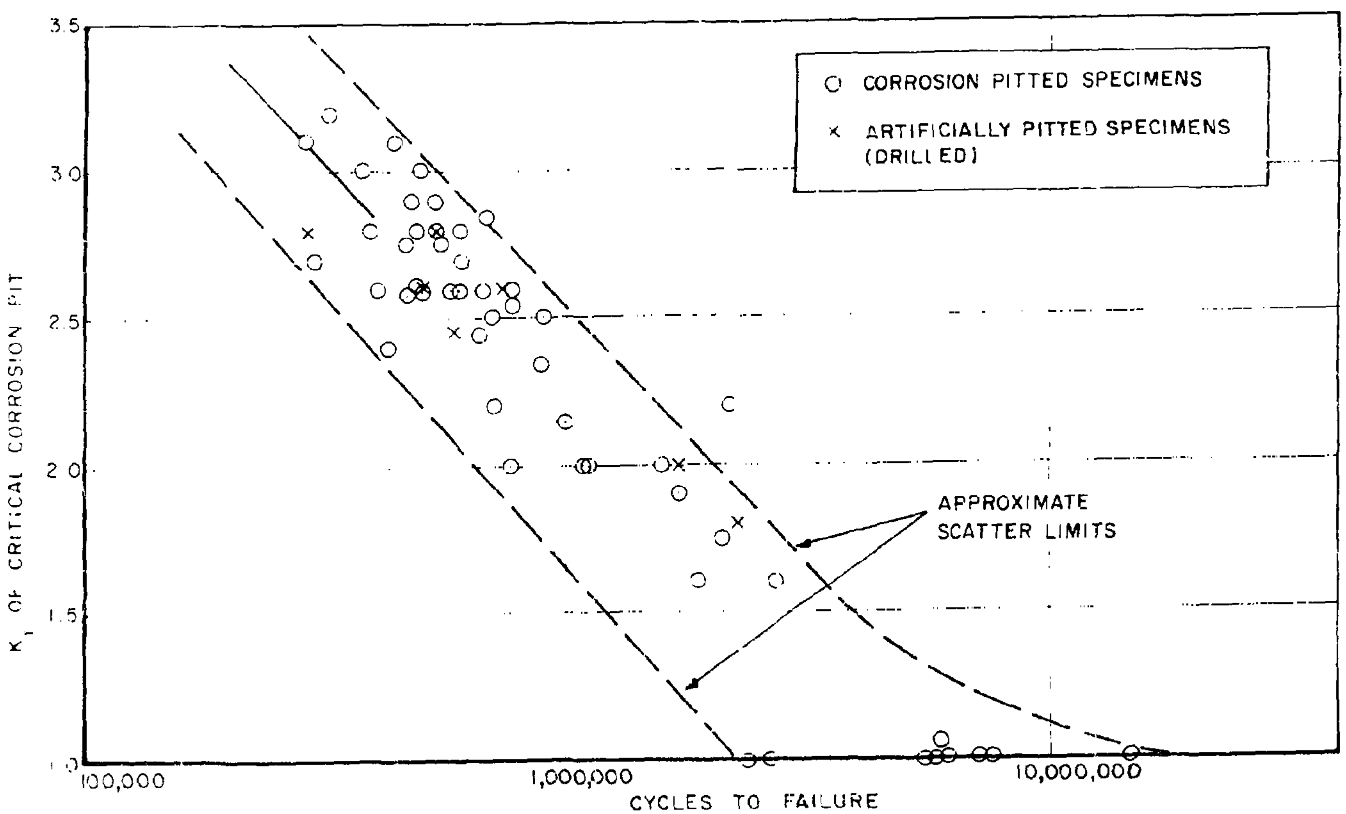

Figure 20. Relationship Between the Theoretical Pit Stress Concentration Factor of Corroded 2024-T4 Aluminum Alloy Specimens and Their Fatigue Lives at ±26,000 psi

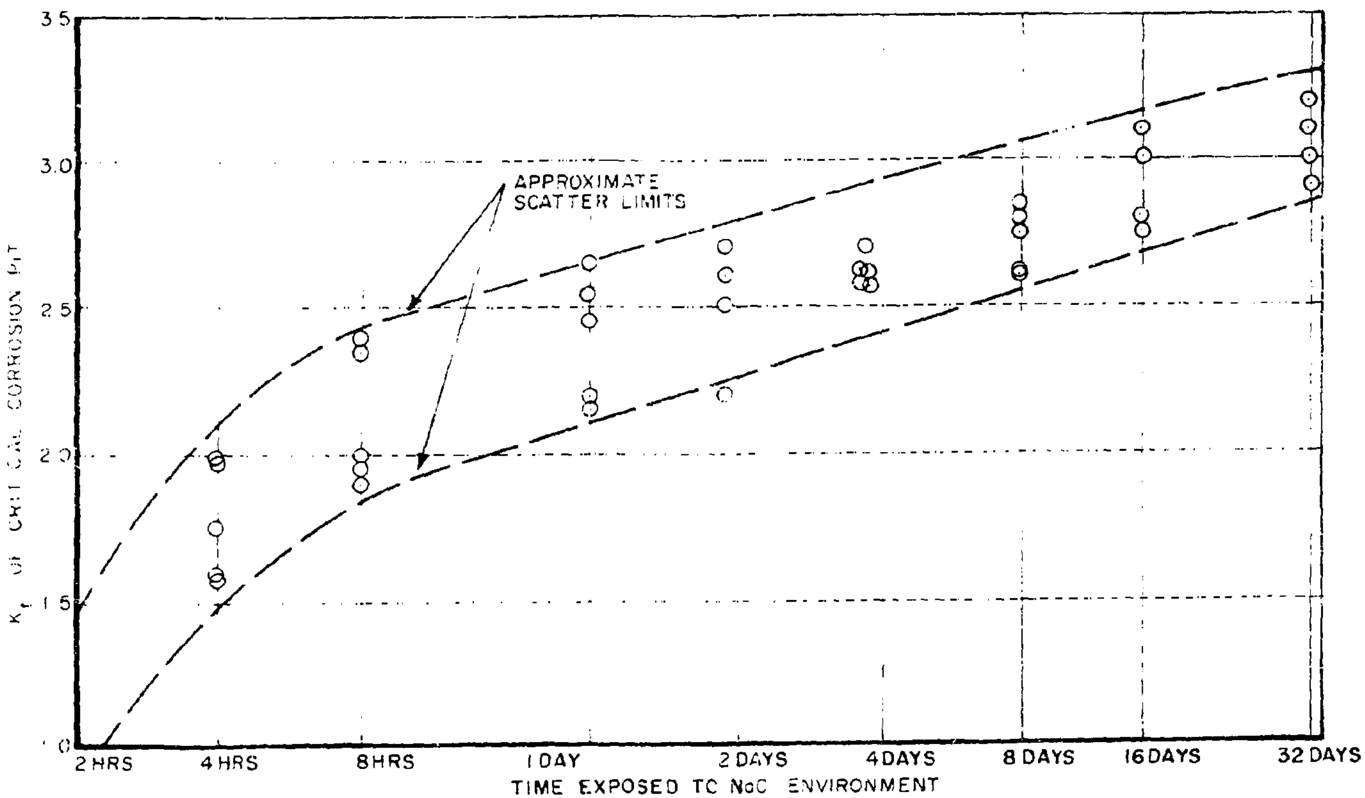

Figure 21. Calculated Theoretical Stress Concentration Factor of the Critical Corrosion Pit of 2024-T4 After Various Exposure Periods